BELLCOMM, INC.

SUBJECT: Evaluation of Space Navigation Techniques for Manned Mars Flyby Mission - Case 103-2

DATE: March 6, 1967

FROM: J. E. Volonte

ABSTRACT

Space navigation techniques are evaluated in terms of the expected capability of meeting the planetary entry requirements of an MSSR probe launched from a manned flyby spacecraft on a 1975 Mars flyby mission. Assuming that continued improvement in the knowledge of the ephemerides of the near planets will permit positioning Mars and earth in the solar system with negligible uncertainty, the following preliminary conclusions can be drawn as guides for subsequent analysis of the 1975 Mars flyby mission: 1) celestial navigation, using only angles between lines of sight to the sun, planets and stars, will not be adequate; 2) the technique of optically measuring apparent planetary diameter to determine range to the planet will not be suitable, but further effort to improve the hardware state-of-the-art appears warranted; 3) the use of optical instruments to measure Mars/star angles will be suitable for determining a single line of position, the accuracy of which would be improved by successful completion of the current development of a planetary center tracker; and 4) depending on the data processing techniques and orbit determination program used, the Deep Space Network of the 1970's may be capable of meeting the total navigation requirements or of providing a surface of position which can be used in combination with a line of position determined optically.

The sensitivities of the entry angle to variations in trajectory determination parameters have been derived for a typical Mars flyby trajectory in which the vehicle has a velocity relative to Mars of 8.75 km/sec (28,700 ft/sec) at a distance of 200 planetary radii.(2) These sensitivities are translated into the approximate allowable errors shown in Table I; each of the tabulated values represents the total allowable for the navigation, guidance and control functions. It should be noted that the errors indicated are all in the orbital plane and that no consideration has been given to cross-track errors.

III. NAVIGATION TECHNIQUES

The space navigation techniques which are discussed in the literature for a 1975 Mars flyby mission are:

Celestial navigation - the on-board optical observation of the stars, sun and planets to determine position in the solar system and, from a knowledge of the position of Mars in the solar system, the computation of vehicle position and velocity relative to Mars.

On-board tracking - the use of on-board optical instrumentation to track Mars directly to determine position and velocity relative to the planet.

Ground-based tracking - the use of earth-based radio/radar instrumentation to track the spacecraft relative to earth and, from a knowledge of the position of Mars with respect to earth, the computation of vehicle position and velocity relative to Mars.

IV. Celestial Navigation

The celestial navigation techniques which have been suggested for the flyby mission include: 1) the measurement of angles between the lines of sight from the spacecraft to celestial bodies to determine a position, a line of position, or surface of position, and 2) a star-occultation observation to determine a line of position. Since the latter technique is dependent on the availability of identifiable stars, suitably located, at the time of obtaining a navigation fix, it will not be considered here further as a primary means of navigation. Celestial navigation, using only angles between the lines of sight from the spacecraft to celestial bodies, requires that two near bodies such as the sun or a planet be used as references.[(3)] This poses a problem since, during the terminal stages of the Mars approach phase, the spacecraft virtually lies on a straight line between the sun and the planet. Aside from the practical difficulties associated with measuring angles of about 180° from a spacecraft, the use of both the sun and Mars as the near bodies fails to provide the unique information necessary to obtain a navigation fix. The use of either sun/stars or Mars/stars would identify two lines of position for the spacecraft; knowledge of approximate position would permit rejection of one of the lines. The use of both near bodies during a set of observations would provide a low-quality fix derived from the intersection of two nearly parallel lines. As a result, obtaining a navigation fix with this technique would require the use of the earth, or other planet, as a second near body.

The accuracy of celestial navigation techniques depends on uncertainties in 1) the knowledge of the positions and motions of celestial bodies, 2) celestial observations made with optical instruments, and 3) the measurement of time. The first two of these are discussed in the following paragraphs with a view toward assessing their impact on a 1975 Mars flyby mission; the third is not covered further since it is expected that clock errors, using ground updating if necessary, will be negligible.

A. Ephemeris Errors

The ephemeris data regarded by the International Astronomical Union (IAU) as the best currently available permit positioning Mars and earth to within 0.1 arc second in the heliocentric coordinates of latitude and longitude.[(4)] That angular uncertainty amounts to a linear uncertainty of approximately 73 km in two orthogonal directions at a distance of 1 astronomical unit (AU).

Knowledge of the radial positions of the planets, however, is less accurate because of the uncertainty in the length of the AU, and while there is no general agreement on a valid figure, the literature contains one-sigma estimates ranging from ±100 to ±500 km. The IAU recognizes an uncertainty of ±2000 km,[4] but the manner of specification suggests that this is a many-sigma value which is not inconsistent with the one-sigma figure of 400 km used by the Apollo Program in Natural Environment and Physical Standards for the Apollo Program.[5] Preliminary analysis of Mariner IV data by JPL shows a reasonable fit during the encounter orbit using an uncertainty of ±240 km[6], and a recent paper[7] based on JPL analysis of data taken over a period of years provides an estimate of ±100 km. In discussion with JPL personnel[8], it was learned that they predict improvement in the AU uncertainty to a one-sigma figure of less than 10 km by 1975, the reduction being achieved primarily through analysis of data obtained on interplanetary missions in the intervening years. Pending completion of the evaluation of Mariner IV data, it is difficult to estimate the validity of this prediction.

B. Observational Errors

There is currently little expermental data on which to base estimates of the accuracy of optically measuring from a spacecraft the angles between lines of sight to celestial bodies.* The consensus, however, appears to be that the state-of-the-art of the next few years will provide a measurement uncertainty having two random, independent components, one a 10 arc second component associated with instrument precision and operator ability and the other, a component which reflects the degree of difficulty in using a body which is not a point source of light.

*Evaluation of the data obtained during the hand-held sextant experiment (T 002) during Gemini GT-12 is now being carried out at the Ames Research Center. Preliminary results are that, for four sets of star-star observations made under the same conditions of astronaut environment, the one-sigma deviations from values determined from a ground track of the spacecraft ranged from 4.5 to 9.0 arc seconds with biases of from -1.8 to +5.8 arc seconds.[8][9]

For the latter, a value of 0.001 times one-half of the angle subtended by the body has been suggested[10] and has been used in a number of space navigation analyses. While analytically convenient, this relationship is not substantiated for relatively large subtended angles by the results of earth-based observations made at the Ames Research Center.*

To overcome what may be a significant uncertainty in measuring angles with respect to a body as large as a near planet, both Ames and JPL have undertaken projects to develop trackers which continuously determine the center of an extended disc. These are not strictly optical devices but are discussed here since, in combination with optical systems, they would be useful on planetary missions. The Ames effort is being carried out under a contract with Lockheed and is described in Reference 11. The intent is to provide an instrument which scans the edge of a planet and electronically computes the geometric center; expected accuracy is about 1 arc second for planets subtending from 10 to 60 arc seconds. A bread-board model has been fabricated at the Lockheed plant, Sunnyvale, but additional development is required.

The JPL tracker which is being proposed for a feasibility demonstration flight test in 1969[8], scans the limb of the planet, and assuming a spherical body, calculates the center. The accuracy goal is a 3-sigma deviation of 0.1 milliradian with a bias of 3 milliradians. The JPL tracker is intended for use at encounter ranges, whereas the Ames instrument is aimed at longer range measurements.

The effect of the foregoing observational uncertainties on celestial navigation in the vicinity of Mars using the earth, sun and stars as references can be determined using the approach taken by Battin,[3] in which he minimizes the rms errors by optimum

*Using a theodolite to measure star-Moon angles, the following deviations are typical:[8]

Star-star angle - 9 arc seconds
Star-limb angle - 15 arc seconds
Star-landmark angle - 20 arc seconds

selection of stars. For the 1975 mission the following conditions would exist at Mars encounter:

Spacecraft-sun distance $\approx$ 1.6 AU

Spacecraft-earth distance $\approx$ 0.8 AU

Earth-spacecraft-sun angle $\approx$ 30°

Apparent angular diameter of earth $\approx$ 22 arc seconds

Apparent angular diameter of sun $\approx$ 1200 arc seconds

Under these conditions and assuming availability of the best planet tracker, the minimum one-sigma position errors of a set of observations consisting of earth-star, earth-star and sun-star angles would be approximately 26,000 km. Replacing the sun by Mars to take advantage of its nearness would roughly halve that error. Reduction of the observational uncertainty to an rms value of 1 arc second would reduce the minimum position errors to approximately 10 percent of the values cited above, reflecting the strong influence of interplanetary distances.

The use of similar equipment to make Mars-star observations only would yield a line of position whose displacement errors are inversely proportional to the distance from Mars. The one-sigma error contribution of each measurement will be small, ranging from approximately 60 km at a planetary distance of 10^6 km to less than 1 km at 10^4 km.

V. On-board Tracking

It has been suggested in a number of papers that during the approach and encounter phases a planet can be tracked optically to measure the angular position and distance of the spacecraft relative to the planet. Angular position is determined by maintaining an optical line of sight to some point on the planet such as a tangent, the center, or a landmark and measuring the angle formed with a reference celestial direction. Distance is measured by using a sextant, theodolite or telescope to determine the angle subtended by the planetary diameter.

To make the required observations it is envisioned that a celestial reference will be established using a stable platform whose alignment will be maintained by star observations. Ideally, a single instrument such as a telescope would be used to determine the angle between the reference and the line of sight to the planet as well as the apparent angular diameter; keeping the telescope on the planet would provide an automatic read-out of the angle, and the optics, possibly in combination with a camera, would measure the angular diameter.

A. Physical Constants Errors

This technique has the advantage of minimizing the need for Mars ephemeris data, but it does introduce the need for knowledge of the diameter of Mars. It is understood that preliminary Mariner IV data indicate an uncertainty in the Mars dimension of about 0.1%.(12) However, the flattening factor for Mars is estimated at 1/190 and, hence, the polar diameter is some 36 km shorter than the equatorial diameter. Assuming that the astronaut-spacecraft system will be capable of identifying the dimension being tracked, the uncertainty in Mars diameter will be translated into a position error which is 0.1% of the range, all in the radial direction since the effect on angle tracking is negligible.

B. Observational Errors

It is estimated that the state-of-the-art of the next few years will permit establishing and maintaining the celestial reference with a one-sigma uncertainty of 0.01°. The uncertainty in measuring the angle to Mars optimistically will approach the value which represents the accuracy goal of the JPL planet tracker. Hence, the planet tracker should be capable of providing a line of position whose one-sigma errors relative to Mars range from about 180 km at a distance of 10^6 km to 2 km at 10^4 km.

There appears to be little data, however, on which to base an estimate of the capability for measuring the planetary diameter from spacecraft optics.* One source(13) estimates that the diameter can be measured within 1 to 5% although the hardware used is not indicated; another(12) assumes a 0.1° stadiametric measurement error. Discussion with JPL and Ames optical navigation personnel revealed, however, that they consider the diameter measurement scheme impractical and that it should not be relied upon as a primary means of navigation. It is clear that the technique poses observational difficulties and that better accuracy than the foregoing estimates would be required. As an example, at a range as close as 10^5 km, Mars would subtend an angle of about 4°, and a measurement error of 0.1° (or 2.5%) would result in a range error of about 500 km.

VI. Ground-Based Tracking

Evaluation of the technique of tracking the spacecraft from earth to provide the necessary navigation data is based on use of the NASA Deep Space Network (DSN), which has already been employed on such planetary missions as Mariner IV. The network uses precision doppler tracking at S-Band frequencies and data reduction and analysis to determine the orbit parameters of the spacecraft being tracked. While primarily a range rate measuring system, the network can be used to obtain the range and angular position of a vehicle relative to the earth-based tracking station, high-order accuracy being achieved through uninterrupted tracking over a period of hours.

The spacecraft navigation error relative to Mars resulting from operation of the DSN for the flyby mission would include the following components: 1) ephemeris errors discussed under Section IV-A. above; 2) uncertainties in the positions of the tracking stations relative to the geocenter, estimated at ± 30 m(14) and considered negligible; and 3) system observational errors, including those associated with uncertainty in the knowledge of the speed of light.

A. Observational Errors

It is understood that prior to a 1975 mission the DSN will have been upgraded to provide a greater capability than has been available in the past. A

*Obtaining the necessary data once the hardware is available should be possible under the Apollo and AAP Programs since at earth distances the Moon will have the apparent angular diameter shown by Mars to an observer approximately 7.6×10^5 km away. Similarly, at the Moon, the earth would present a target comparable in size to Mars at a distance of approximately 2×10^5 km.

recent estimate of the capabilities expected at distances of 1 AU includes a two-way doppler tracking accuracy of at least 0.001 m/s (with 0.0002 m/s probable) and ranging accuracy of 10 meters.(15) Comparison of these figures with other performance data on the system suggests that they are one-sigma figures which do not reflect the uncertainty in the knowledge of the speed of light. However, the doppler frequency shift expected at S-band frequencies for the 1975 Mars mission is sufficiently small that the speed of light uncertainty will not significantly degrade the range rate measuring capability.

Discussion with JPL personnel(8) provided the following "conservative" estimate of the expected angle tracking accuracy of the DSN at interplanetary distances in the mid-1970's:

Geocentric declination - 0.04 arc seconds
Geocentric right ascension - 0.03 arc seconds

The estimate of system ranging capability was made in terms of light-seconds, a unit which is independent of the speed of light but which cannot be applied directly to this analysis. Assuming no significant improvement in the uncertainty in the knowledge of the speed of light, the one-sigma estimate of $\pm$100 m/s used in the Apollo Program would result in a range error of about $\pm$80 km at encounter distances for the mission under consideration. The overall observational errors in using the DSN directly as a position-determining system would have a one-sigma value somewhat in excess of $\pm$80 km.

VII. Evaluation of Space Navigation Capability

In the preceding assessment of the capabilities of the various navigation techniques primary attention has been devoted to the determination of spacecraft position relative to Mars. The computation of velocity from position data is generally dependent on the data processing and analysis techniques used, and random, independent errors can be reduced by appropriate data filtering and analysis. Without pursuing these aspects of the navigation problem further, certain preliminary conclusions can be drawn as guides for subsequent analysis and study of the 1975 Mars flyby mission:

1. Celestial navigation, using only angles between lines of sight to the sun, planets and stars to determine position, will not be adequate. Even with the elimination of all ephemeris errors and the reduction of observational uncertainties to the order of 1 arc second rms, the position errors, which are generally independent of distance from Mars, are well in excess of allowable.

2. Within the present and near-future state-of-the-art, the often-suggested technique of optically measuring apparent planetary diameter to determine range to the planet does not appear to be suitable for the task. The apparent simplicity of the concept and its independence of ephemeris uncertainties, however, suggest that it be continued under study and that some effort be made to determine suitable hardware innovations.

3. The use of optical instruments to measure star/Mars angles will, with expected improvement in ephemeris data, afford a suitable means of establishing one line of position whose errors relative to Mars will be within allowable limits. Use of a planetary center tracker in combination with the optics should improve the accuracy of such a line of position. Similarly, the planet tracker when operated with an appropriate celestial reference determination technique should meet the requirements; this method has the advantage of eliminating the effects of ephemeris errors, but errors in establishing the celestial reference are introduced. For these techniques an additional line or surface of position is required to provide a navigational fix.

4. Assuming continued improvement in the knowledge of the ephemerides of earth and Mars, the DSN of the 1970's may be capable of meeting the navigation requirements at encounter ranges. Further analysis of the data processing techniques and orbit determination program is required to fully evaluate the

overall system capability for performance of the total navigation function or determination of a surface of position which can be used in combination with a line of position determined optically.

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Attachment
Table I

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TABLE I

Allowable Errors in Trajectory Determination Parameters*

	Allowable Errors				
		Velocity			
Range to Planet (km)	Range (km)	Total (m/sec)	Radial (m/sec)	Tangential (m/sec)	Flight Path Angle (°)
10^6	2400.	89.	89.	0.4	0.0005
10^5	240.	93.	93.	3.8	0.005
10^4	24.	149.	137.	54.0	0.05

*The allowable error values are all ± and represent the maximum deviations from the nominal probe trajectory which can be allowed at the ranges indicated to keep the MSSR entry angle within ±0.4° of a nominal value of -19° at an altitude of 220 km. The values have been rounded off to facilitate comparison.